Combined-Cycle Gas and Steam Turbine Power Plant Reliability Analysis

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Abstract The reliability and availability of the combined-cycle thermal power plants depends on the perfect operation of all its systems (e.g. gas turbine, heat recovery steam generator, steam turbine and cooling system). The Heat Recovery Steam Generator (HRSG) is the link between the gas turbine and the steam turbine process having the function of converting the exhaust gas energy of the gas turbine into steam. In the cooling water system, heat removed from the steam turbine exhaust in the condenser is carried by the circulating water to the cooling tower, which rejects the heat to the atmosphere. This chapter presents reliability and availability analysis of a 500 MW combined-cycle thermal power station aiming at defining the most critical components of the main pieces of equipment as for power plant availability. The cooling tower cells are detailed evaluated in order to improve there availability through risk analysis and reliability centered maintenance concepts.

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1 Introduction

The performance of any power plant can be determined by four elements:

(a) Capability to satisfy functional needs;
(b) Efficiency to effectively utilize the energy supplied;
(c) Reliability to start or continue to operate;
(d) Maintainability to quickly return to service after one failure.

It is evident that the first two measures are influenced by the design, manufacturing, construction, operation, and maintenance. Capability and efficiency reflect how well the power plant is designed and constructed. On the other hand, the last two measures, reliability and maintainability, are operations-related issues and are influenced by the power plant potential to remain operational and the efficiency of the repair aiming at returning to service process. It would be conceivable to have a power plant that is highly reliable, but does not achieve high performance.

Usually the power plant performance analysis is based on thermodynamic parameters evaluation in order to define the plant operational efficiency.

The ASME PTC 46 [1] code can be used to measure the performance of a plant in its normal operating condition, with all equipment in a clean and fully-functional condition. The analysis is based on key performance index and the most important one is the heat rate. This code provides explicit methods and procedures for combined-cycle power plants and for most gas, liquid, and solid fueled Rankine cycle plants. The scope of this code begins for a gas turbine based power generating unit when a heat-recovery steam generator is included within the test boundary. To test a particular power plant or cogeneration facility, the following conditions must be met. (a) means must be available to determine, through either direct or indirect measurements, all of the heat inputs entering the test boundary and all of the electrical power and secondary outputs leaving the test boundary; (b) means must be available to determine, through either direct or indirect measurements, all of the parameters to correct the results from the test to the base reference condition; and (c) the working fluid for vapor cycles must be steam. This restriction is imposed only to the extent that other fluids may require measurements or measurement methods different from those provided by this code for steam cycles. In addition, this Code does not provide specific references for the properties of working fluids other than steam. Tests addressing other power plant performance related issues are outside the scope of this code such as Reliability tests, which are tests conducted over an extended period of days or weeks to demonstrate the capability of the power plant to produce a specified minimum output level or availability. The measurement methods, calculations, and corrections to design conditions included herein may be of use in designing tests of this type; however, this code does not address this type of testing in terms of providing explicit testing procedures or acceptance criteria.

The most widely accepted definition of reliability is “the ability of an item, product, system, etc., to operate under designated operating conditions for a designated period of time or number of cycles”. The ability of an item to start or

continue to operate can be designated through a probability (the probabilistic connotation), or can be designated deterministically.

The deterministic approach, in essence, deals with understanding how and why an item fails, and how it can be designed and tested to prevent such failure from occurrence or recurrence. This includes analysis such as review of field failure reports, understanding physics of failure, the role and degree of test and inspection, performing redesign, or performing reconfiguration. In practice, this is an important aspect of reliability analysis.

Reliability has then two connotations. One is probabilistic in nature; the other is deterministic. In this chapter, we deal with the probabilistic aspect of power plant operational performance.

It should be noted that reliability is also tightly related to operational safety, especially for nuclear power plants and other industrial applications that imply important risks for workers, public and environment. But these issues are not discussed within this chapter.[1]

The availability of a complex system such as a thermal power plant is strongly associated with the parts reliability and maintenance policy. That policy not only has influence on the parts repair time but also on the parts reliability affecting the system degradation and availability, [16].

Availability is a measure of percentage of time in which a plant is capable of producing its end product at some specified acceptable level. In a simple way, availability is controlled by two parameters, IEEE [12]:

- Mean time to failure (MTTF) which is a measure of how long, on average, the plant will perform as specified before an unplanned failure occurs, being associated with equipment reliability;
- Mean time to repair (MTTR) which is a measure of how long, on average, it will take to bring the equipment back to normal serviceability when it does fail.

Although reliability can be at least estimated during the plant design stages, its availability is strongly influenced by the uncertainties in the repair time. Those uncertainties are influenced by many factors such as the ability to diagnose the cause of failure or the availability of equipment and skilled personnel to carry out the repair procedures.

Eti, Ogaji and Probert [8] presented an approach for the integration of reliability concepts and risk analysis as guidance in maintenance policies for the Afam thermal power station. Those authors do not present the results expected or obtained with the application of those concepts.

A combined-cycle power plant is a combination of a fuel-fired turbine with a HRSG and a steam powered turbine. These plants are very large, typically rated in the hundreds of mega-watts. The use of combined-cycle power plants aims at using in the most efficient way the fossil fuels burned in turbine, typically natural gas or fuel oil, considered as nonrenewable energy resources.

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[1] For reliability safety issues, see [11].

There are basically two general arrangements in combined cycle power plants, which are:

- Single-shaft: the combustion turbine and steam turbine drive a common generator in a tandem configuration, with only one HRSG. Single-shaft arrangement uses common systems for both turbines such as lubrication oil, simplifying the power plant auxiliary system complexity and maintenance planning.
- Multi-shaft: the combustion turbine and the steam turbine are coupled to a proper generator. Typically an arrangement with two gas turbines, two HRSGs and one steam turbine is used. Depending on the power requirements at the time, the multi-shaft combined cycle plant may operate only the fired turbine and divert the exhaust. However, this is a substantial loss of efficiency. Large fired turbines are in the low 30% efficiency range (although some manufacturers declares the possibility of operating heavy-duty gas turbines with efficiency close to 45%), while combined cycle plants can exceed 60% efficiency.

In the present chapter a multi-shaft combined-cycle power plant is analyzed.

The reliability and availability of the combined-cycle thermal power plants depends on the perfect operation of all its systems (e.g. gas turbine, heat recovery steam generator, steam turbine and cooling system).The HRSG is the link between the gas turbine and the steam turbine process, the function of HRSG is to convert the exhaust gas energy of the gas turbine into steam, Kehlhofer [13]. In the cooling water system, heat removed from the steam turbine exhaust is carried by the circulating water to the cooling tower, which rejects the heat to the atmosphere. Because of this direct path to the atmosphere, surrounding water bodies typically do not suffer adverse thermal effects. Cooling towers have been used for many years at power plants in locations where some water is available for cooling system use. The recirculating cooling water system arrangement incorporates an evaporative cooling tower as show in Fig. 1, [3].

2 Method of Reliability Analysis

The method first step consists in the elaboration of the functional tree for each piece of equipment installed in the power plant. The functional diagram allows the definition of the functional links between the equipment subsystems.

The next step is the development of the Failure Mode and Effects Analysis (FMEA) of each power plant equipment component in order to define the most critical components for plant operation. This criticality is based on the evaluation of the component failure effect on the system operation, [15]. For the definition of the system degradation, the FMEA analysis uses a numerical code, usually varying between 1 and 10. The higher the number the higher is the criticality of the component that must be evaluated for each component failure mode. For the plant analysis a criticality scale between 1 and 9 is proposed, [4]. Values between 1 and 3 express minor effects on the system operation and values between 4 and 6

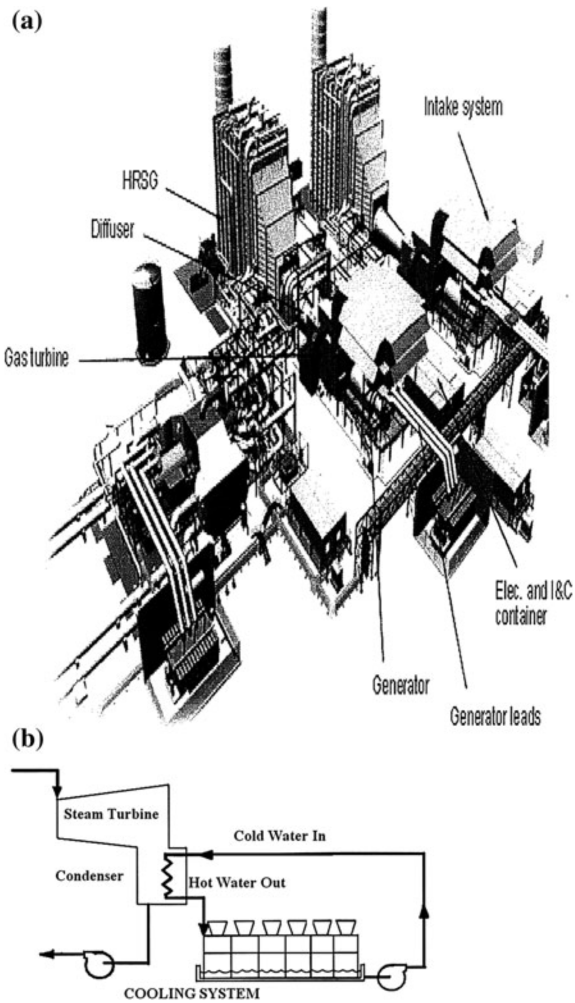


Fig. 1 Typical combined cycle thermal power plant general arrangement [3] **a** Power generation. **b** Cooling systemSystem

express significant effects on the system operation. Failures that cause the combined-cycle unavailability or environmental degradation are classified with criticality values between 7 and 9. These criticality values are shown in Table 1.

The method third step involves a reliability analysis. The failures should be classified according to the subsystem presented in the functional tree. The reliability of each subsystem is calculated based on the failure data base and the system reliability is simulated through the use of block diagram. Considering the 'time to repair' data and the preventive maintenance tasks associated with the equipment, the availability is evaluated using the block diagram.

Once the critical components are defined a maintenance policy can be proposed for those components, considering the RCM concepts. This maintenance policy philosophy has focus on the use of predictive or preventive maintenance tasks

Table 1 Criticality index description for FMEA analysis [4]

Criticality index	Effects on the turbine operation
7 (Severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but does not cause damage to other equipment components, possibly affecting:–the equipment operation, once it must be stopped;–the environment in a severe manner;–the compliance with government requirements. The failure also causes the need of repair and/or replacement of the failed component. The plant is unavailable for short period of time.
8 (Very severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but do not cause damage to other equipment components, possibly affecting:- the equipment operation, once it must be stopped;–the environment in a severe manner;–the compliance with government requirements. The failure also causes the need of repair and/or replacement of the failed component. The plant is unavailable for long period of time.
9 (Hazardous effects)	This severity ranking is given when a component potential failure mode can cause severe damage to other components and/or to the equipment, possibly affecting:- the equipment operation, once it must be stopped;- the environmental safety, including leakage of hazardous materials;–the safe power plant operation;–the compliance with government requirements. The failure also causes the need of repair and/or replacement of a great number of components. The plant is unavailable for long period of time.

that aim at the reduction of unexpected failures during the component normal operation, Smith and Hinchcliffe [16]. For complex systems, the occurrence of unexpected components failures highly increases maintenance costs associated with corrective tasks not only for the direct corrective costs (spare parts, labour hours) but also for the system unavailability costs.

So, the use of predictive or preventive tasks allows the programming of maintenance tasks in advance and also reduces the component failure probability during a given operation period and consequently increasing the system availability.

The reliability block diagram analysis not only allows the evaluation of the actual maintenance policy but also allows the prediction of possible availability improvement considering the application of new maintenance procedures, expressed by the reduction of corrective maintenance repair time.

In Fig. 2 a flowchart is used to explain the method's main steps [4].

3 Application

The method is applied on the analysis of a set of equipment installed in a 500 MW multi-shaft combined cycle thermoelectric power plant located in South America.

The plant uses two class F heavy duty gas turbines with nominal output close to 150 MW. The steam turbine, with three pressure levels is capable of generating nominal output higher than 200 MW.

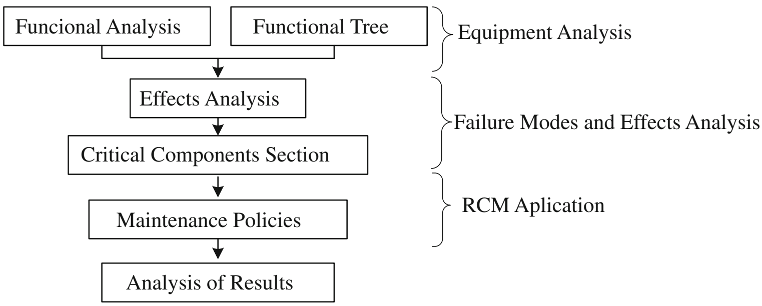


Fig. 2 Flowchart for complex system availability evaluation, Carazas and Souza [4]

The power plant HRSGs consist of three major components, which are Evaporator, Superheater, and Economizer. The equipment is classified as horizontal type HRSGs once the exhaust gas flows horizontally over vertical tubes, named harps. The equipment is also a triple pressure HRSG, presenting three sections: an LP (low pressure) section, a reheat/IP (intermediate pressure) section, and an HP (high pressure) section.

The power plant uses a condenser and a set of ten counter flow cooling towers that are independently operated.

Aiming at keeping the power plant output in the summer hottest days, an evaporative cooling system is installed in the inlet of both gas turbines aiming at reducing inlet air temperature and consequently controlling the turbine efficiency. The basic operation of the evaporative cooling system is based on the circulation of water through a heat exchanging media. Water is pumped from a tank to a header above the heat exchanging media. A spray system wets the top of the media. The water flows in the channels in the media, which are made of corrugated layers of fibrous material. The water flows down by gravity through the channels, wetting the material of the walls. The air absorbs the water which evaporates from the wall.

3.1 Functional Tree Development

The functional tree is developed for each piece of equipment installed in the power plant.

The functional tree for the gas turbine was presented in Chap. 8. In Figs. 3 and 4 the functional trees for the HRSG and steam turbine are respectively presented. In Fig. 5 the functional tree for the cooling system is presented, including condenser and cooling tower.

The main pieces of equipment of a combined cycle power plant, such as gas and steam turbine, HRSG and condenser have basic design characteristics but there might be some specific design features in the piece of equipment installed in a

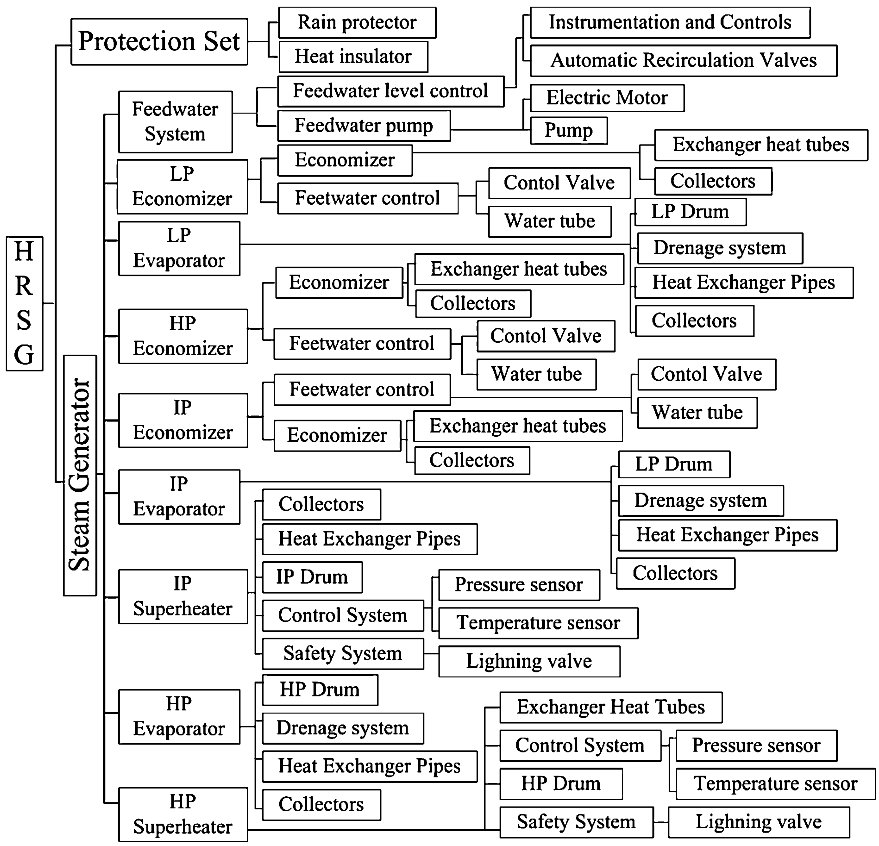


Fig. 3 HRSG functional tree, Carazas and Souza [6]

given power plant. So it is recommended that the functional tree must be developed for the equipment that composes the power plant under study.

Although all cooling tower possess essentially the same subsystems, such as circulating water pumps, circulating water piping and fans, there are differences between the technologies used by the manufacturers; therefore the functional tree must be developed for each specific cooling tower model. Specifically for the cooling tower under analysis, for each cell, the fan gearbox is located inside the cooling tower cell with the vertical output shaft below the fan.

The FMEA analysis was performed for each component listed in the end of a given branch of the functional tree. As for example, in Table 2 the critical components of the HRSGs are presented, Carazas, Salazar and Souza [6] and in Table 3 this analysis is executed for the cooling towers cells, Carazas and Souza [5].

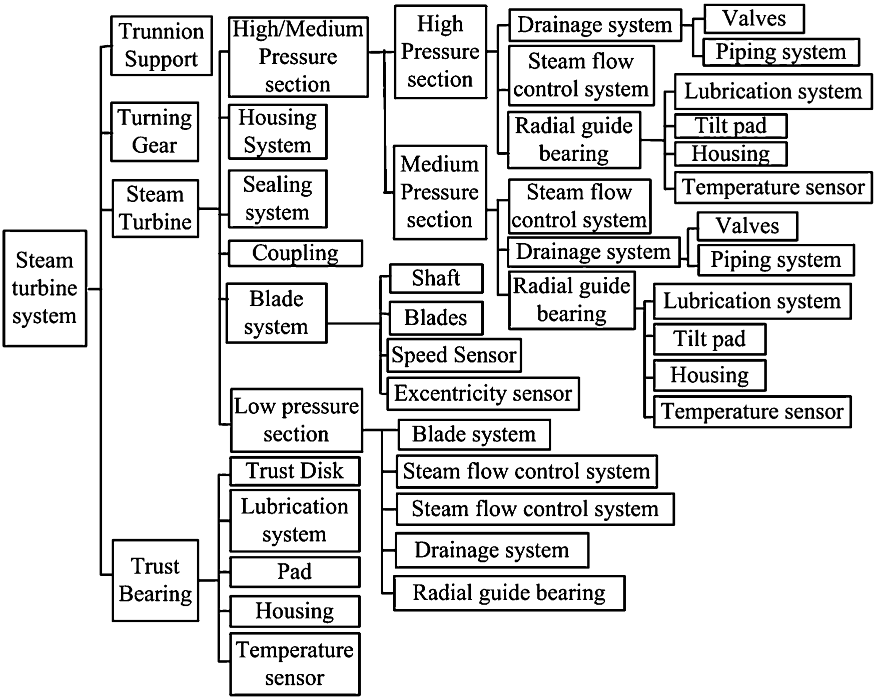


Fig. 4 Steam turbine functional tree

3.2 *Reliability Analysis*

The power plant must be modeled according to the reliability block diagram presented in Fig. 6. The power plant is a series system except for the cooling tower that is modeled as K out of N systems, meaning that it is necessary a given number of cooling towers units working (K) out of 10 to allow the plant to achieve nominal output.

Aiming at keeping the power plant nominal output during all year, the number of cooling towers units in operation must vary during the calendar year due to climate seasons.

The power plant site location presents low average temperature in winter (around 14°C), medium average temperature in autumn and spring (around 22°C) and high average temperature in summer (around 30°C). Based on the weather conditions, Table 4 presents the number of cooling tower units that must be operated to keep plant nominal output.

The cooling tower system operational strategy consists on using nine units and one unit is considered redundant equipment. During autumn and spring that operational strategy is being adopted by the plant operator. During winter, due to

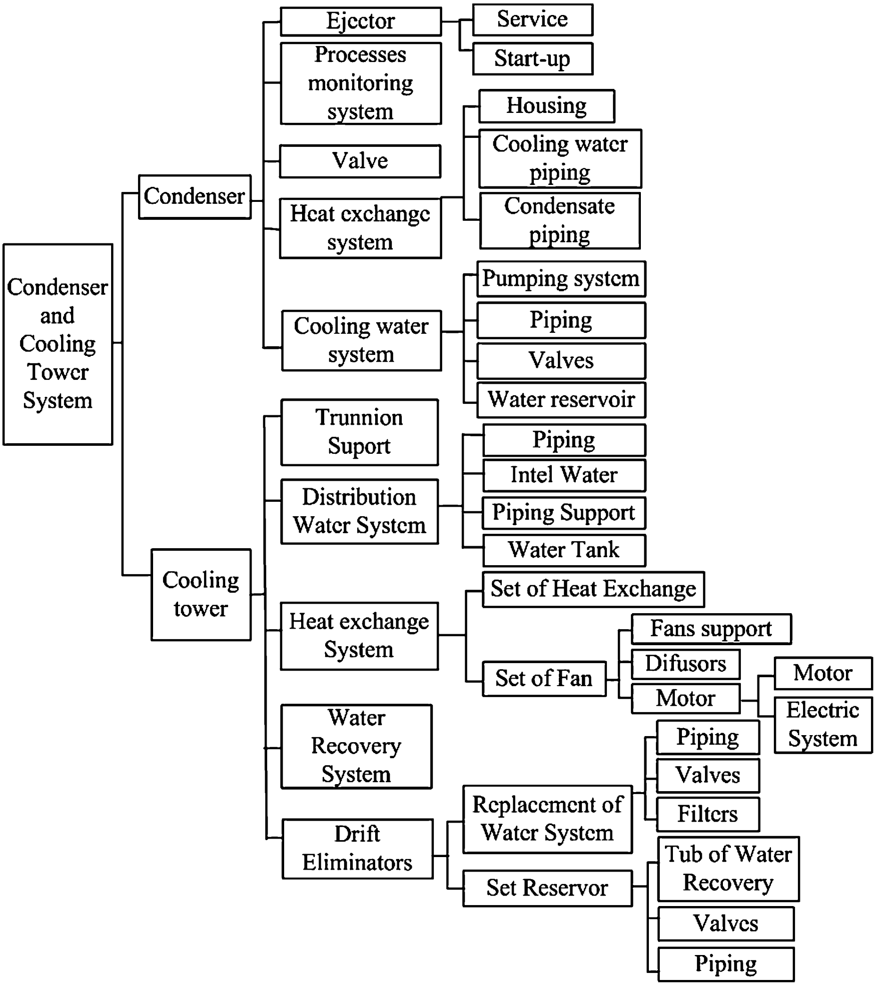


Fig. 5 Condenser and cooling tower functional tree, Carazas and Souza [5]

low air temperature, the cooling tower system can operate with 8 units without affecting the power plant nominal output.

During summer, the cooling tower system must operate with all ten units. The failure of any unit affects the power plant output. In some very hot days during summer it must be necessary to use an evaporative cooling system installed in the gas turbine inlet aiming at controlling turbine efficiency and heat rate to allow the power plant to deliver the nominal output.

The electrical generators coupled to each turbine are not considered in the present analysis which main focus is the evaluation of the influence of complex mechanical pieces of equipment in the power plant reliability. If those generators

Table 2 Critical components for HRSGs, Carazas, Salazar and Souza [6]

	Events	Critical components
1	Loss of the water flow in IP and HP evaporators	Feedwater pump. Water tube. Heat exchanger tubes (harps). Valves.
2	Dangerous increase in steam pressure inside Drums	Feedwater pump. Water tube. Heat exchanger tubes (harps). Control valves. Drainage system. Control system.
3	Increase in steam pressure in the HP system	Feedwater pump. Water tube. Heat exchanger pipes (harps). Control valves. Control system.
4	Loss of pressure control in the HP superheater	Water tube. Heat exchanger tubes (harps). Control system
5	Critical increase of the steam pressure	Water tube. Collectors. Heat exchanger tubes (harps). Control valves. Control system.
6	Rupture of the collectors and/or heat exchanger pipes	Collectors. Heat exchanger tubes (harps)
7	Feedwater pump failure	Check valve Electrical motor Pump

are considered in the analysis they should be represented by blocks added in series to the block diagram shown in Fig. 6.

The variation in the power plant configuration must be considered in the reliability analysis.

Reliability can be defined as the probability that a system will perform properly for a specified period of time under a given set of operating conditions. Implied in this definition is a clear-cut criterion for failure, from which one may judge at what point the system is no longer functioning properly. For the power plant analysis the failure criterion is any component failure that causes incapacity of generating the nominal power output.

The reliability analysis is performed for each of the pieces of equipment installed in the power plant, submitted to the same commissioning process and starting to operate at the same time. The reliability analysis is based on the time to failure data analysis.

Table 3 Critical components for cooling tower cell, Carazas and Souza [5]

Event	Component	Failure mode
Loss of cooling capacity	Structure support	Achieve ultimate limit state
	Distribution water system	
	Piping	Cross section blockage
	Inlet water	Cross section blockage
	Heat exchange system	
	Electric motor	No electric power
	Flexible shaft	Shaft cross section rupture
	Gear box	Gear tooth fatigue failure
		Shaft cross section rupture
	Coupling	Linkage between coupling and electric motor failure
		Coupling failure
	Water recovery system	
	Check valve	Incapacity to open
	Water piping	Cross section blockage

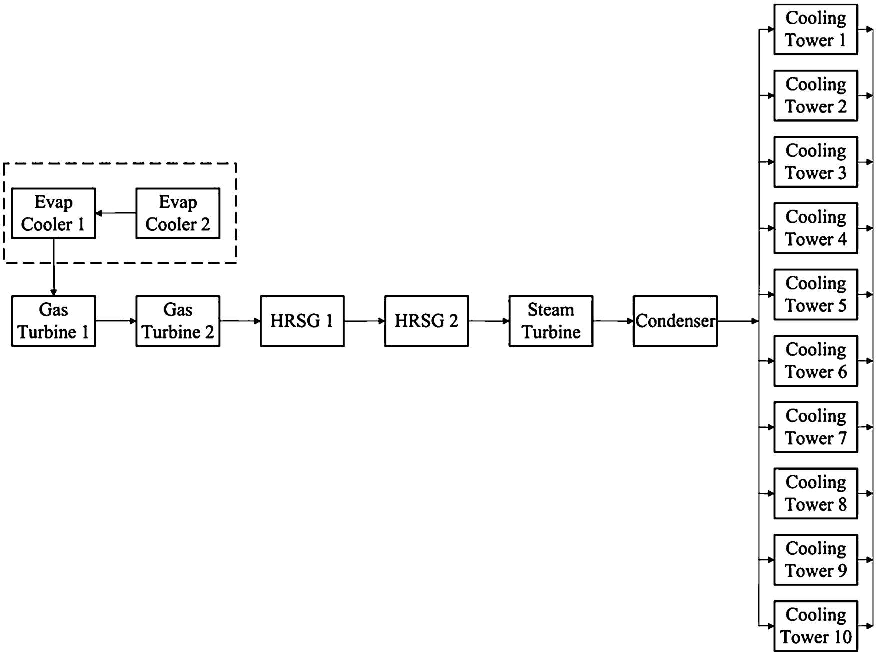


Fig. 6 Reliability block diagram for power station reliability analysis

For complex mechanical equipment such as gas and steam turbine, HRSG and condensers in the beginning of its operational life, it is hard to affirm that the system present random failure, since its performance depends on commissioning and operational procedures and even on environmental conditions.

Table 4 Cooling system configuration

Season	Number of cooling towers	Evaporative cooling system Operational
Summer	10	S[a]
Autumn	9	N
Winter	8	N
Spring	9	N

[a] For some specific weather conditions

When the phenomena of early failures, aging effects, or both, are presented, the reliability of a device or system becomes a strong function of its age. For that case the reliability is modeled through the use of Weibull probability distribution.

The gas turbines and HRSG reliability are modeled based on the use of the two-parameter Weibull distribution. The distribution parameters are estimated through the use of parametric estimation methods that fit the distribution to the 'time to failure' data. There are procedures for estimating the Weibull distribution parameters from data, using what is known as the maximum likelihood estimation method. The analysis of those systems is detailed presented by Carazas and Souza [4] and Carazas, Salazar and Souza [6].

The steam turbine and condenser reliability are also calculated based on ′time to failure′ database provided by the power plant. Taking in view that the technology associated with the design and manufacturing of those pieces of equipment are more mature than the design technology of heavy duty gas turbines, the reliability distribution is modeled with an exponential distribution.

For the cooling towers units and evaporating cooling systems the power plant failure database has not enough information as for reliability analysis. For those systems the reliability is calculated based on reliability database information, according to the studies present by Carazas and Souza [5].

3.2.1 Cooling Tower Unit Reliability

The cooling tower unit block diagram, for normal operation condition, is a series system using all subsystems present in the first level of the functional tree. Once the reliability of each component is defined, based on statistical analysis of their failure data, the cooling tower reliability is equal to the product of the subsystem reliability, as show in Fig. 7, and the system reliability is expressed by the Eq. 1.

$$R_{CT} = R_{SS}.R_{WS}.R_{HE}.R_{WR} \tag{1}$$

where R_{CT} is the reliability of cooling tower, R_{SS} is the reliability of support structure; R_{WS} is the reliability of distribution water system; R_{HE} is the reliability of Heat exchange system and R_{WR} is the reliability of water recovery system. Considering that each subsystem reliability can be modeled by an exponential

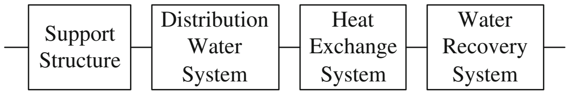


Fig. 7 Cooling tower reliability block diagram

distribution, the cooling tower reliability is also modeled by an exponential distribution which failure rate is calculated as:

$$\lambda_{CT} = \lambda_{SS} + \lambda_{WS} + \lambda_{HE} + \lambda_{WR} \tag{2}$$

where λ_{CT} is the cooling tower failure rate, λ_{SS} is the support structure failure rate; λ_{WS} is the distribution water system failure rate; λ_{HE} is the heat exchange system failure rate and λ_{WR} is the water recovery system failure.

The reliability of those subsystems can be estimated thought the following methods:

- Analysis of the historical failure database of the equipment.
- Analysis of the historical failure database of similar equipments.
- Analysis of prototypes reliability tests.
- Use of reliability prediction mathematical models based on commercial database.

For the present study, the selection of the most critical equipments as for reliability block diagram analysis is based on the failure database of the power plant. The critical components are those that present the greatest frequency of failure.

Unfortunately, the failure database does not clearly register the time between two consecutive failures in a given component that would support equipment reliability analysis. Thus, reliability estimate for the critical components is based on data book information.

The critical components are: support structure, electric motor, gear box and fans. The support structure is subjected to dynamic loading due to fan rotation. Electric motor and the gearbox are subjected to an environment with high humidity and subjected to dynamic loading due to fan rotation.

The simplified cooling tower unit block diagram is shown in Fig. 8.

Table 5 gives a list of the critical components that constitute cooling tower unit and the parameters of the reliability models, MIL-HDBK-217F [7] and Krishnasamy [14].

The cooling tower failure rate is 390×10^{-6} failures per hour.

3.2.2 Evaporating Cooling System

The evaporative cooler installation depends primarily on the plant operational characteristics and location. So the main goal of the present analysis is to evaluate the system reliability based on a standard configuration. That standard config-

Fig. 8 Simplified cooling tower reliability block diagram

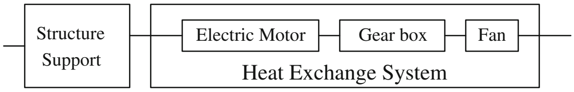


Table 5 Failure rate of cooling tower critical components

Subsystem	Component	Parameter
Structure support	Structure	$\lambda = 31{,}0 \times 10^{-6}$ failures/hour
Heat exchange System	Electric motor	$\lambda = 34{,}2 \times 10^{-5}$ failures/hour
	Gear box	$\lambda = 16{,}0 \times 10^{-6}$ failures/hour
	Fan	$\lambda = 1{,}20 \times 10^{-6}$ failures/hour

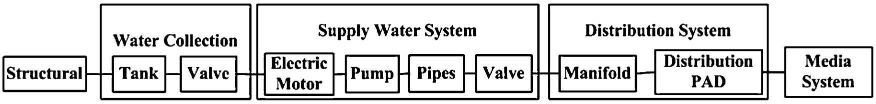


Fig. 9 Evaporative cooler system reliability block diagram

uration must represent the set of equipment that must be installed in any evaporative cooling system.

Taking in view the great number of pieces of equipment in the evaporative cooling system, the reliability cannot be calculated as only one part.

According to Sect. 2, for that kind of system the reliability block diagram is used to calculate system reliability. The proposed reliability block diagram for an evaporative cooling system is presented in Fig. 9. This block represents a generic evaporative cooler, considering the basic subsystems that any of those systems must present. The specificity of a given system must be represented by a new block added to the basic block diagram.

Analyzing the diagram presented in Fig. 9 it is possible to see that the evaporative cooling system is modeled as a series system, so the failure of one of the components will cause the failure of the subsystem. According to the reliability definition the subsystem failure does not only mean the total shut down of the cooling system but also the reduction of its performance. The use of reliability diagram only allows the evaluation of reliability but does not allow the evaluation of the system potential failure modes.

Nevertheless, the evaluation of reliability is important once it represents the chance that the evaporative cooling subsystem will be operational during a given operational period of the thermal power plant. This fact has a direct impact on the possibility that the gas turbine will achieve the predicted efficiency during a specific operational period.

To correctly estimate the evaporative cooling subsystem reliability for a given power plant it would be necessary to access the maintenance planning system

Table 6 Evaporative cooler subsystems reliability distribution

Component	Reliability distribution parameter
Structure	99% constant (estimated)
Water collection	
Tank	Exponential distribution, $\lambda = 2.24 \times 10^{-6}$ failures/hour
Valves	Exponential distribution, $\lambda = 4.7 \times 10^{-8}$ failures/hour
Water supply subsystem	
Pump plus electric motor	Exponential distribution, $\lambda = 10.40 \times 10^{-6}$ failures/hour
Piping system	Exponential distribution, $\lambda = 4.73 \times 10^{-7}$ failures/hour
Valves	Exponential distribution, $\lambda = 4.7 \times 10^{-8}$ failures/hour
Distribution system	
Manifold	Exponential distribution, $\lambda = 6.97 \times 10^{-6}$ failures/hour
Distribution pad	Exponential distribution, $\lambda = 4.7 \times 10^{-8}$ failures/hour
Media system	99%

database aiming at defining the time to failure probability distribution of each component listed in the block diagram. The reliability of those components will allow the evaluation of the evaporative cooling subsystem.

The goal of the present analysis is to estimate the reliability of a generic evaporative cooler and the components reliability can be initially estimated based on database information.

The most famous database as for thermal power plant equipment reliability analysis is the one provided by the North American Electric Reliability Corporation (NERC). That database is a collection of operating information associated with the performance of electric generating equipment, including reliability and availability data.

The database associated with gas turbine does not present any information regarding the failure of evaporative cooling subsystem. So, the reliability analysis for the subsystem presented on Fig. 9 will be based on data presented by the Reliability Analysis Center (RAC). Table 6 presents the probability functions and their parameters used to model the components reliability.

3.2.3 Power Plant Reliability and Availability Analysis

Table 7 shows the reliability and maintainability distribution parameters for each piece of equipment installed in the power plant.

In Table 7 β represents the shape factor of the Weibull distribution, η represents the scale factor of the Weibull distribution in hours, μ represents the mean of the Lognormal distribution, σ represents the standard deviation of the Lognormal distribution, both of them calculated in the logarithm scale, μ_n and σ_n represents respectively the mean and standard deviation of Normal distribution expressed in hours and λ represents the failure rate of the Exponential distribution expressed in failures/hour.

Table 7 Power plant pieces of equipment reliability and maintainability distributions

Equipment	Reliability distribution		Maintainability distribution	
	Distribution	Parameter	Distribution	Parameter
Gas turbine	Weibull	$\beta = 0.95$ η= 2,562.05	Lognormal	$\mu = 1.400$ $\sigma = 0.86$
Steam turbine	Exponential	λ= 0.0007	Lognormal	$\mu = 1.1395$ $\sigma = 2.022$
HRSG	Weibull	$\beta = 0.995$ η= 2,551.84	Lognormal	$\mu = 1.8932$ $\sigma = 0.9314$
Condenser	Exponential	λ= 0.0003	Lognormal	$\mu = 1.8684$ $\sigma = 1{,}5976$
Cooling tower (1 Unit)	Exponential	λ= 0.00039	Normal	$\mu_n = 8$ $\sigma_n = 1$
Evap Cooler	Exponential	λ= 0.000028	Normal	$\mu_n = 2$ $\sigma_n = 0{,}5$

For gas and steam turbines and HRSGs the reliability distribution reflects the preventive maintenance plan suggested by the manufacturer. For example, the gas turbine is subjected to special maintenance tasks according to the following schedule:

- After 8,000, 16,000, 32,000 and 40,000 operational hours the gas turbines are submitted to an inspection in the combustion system. The intervention takes around 7 days;
- After 24,000 operational hours the gas turbines are submitted to an inspection in the hot gas path. The intervention takes around 14 days;
- After 48,000 operational hours the gas turbines are submitted to a major maintenance. The intervention takes around 28 days.

In parallel to the gas turbine maintenance activities, the steam turbine and HRSGs are also submitted to complex preventive maintenance tasks with increasing complexity as a function of the operational hours. Both pieces of equipment are submitted to major maintenance after 48,000 operational hours.

In Fig. 10 the reliability of the power plant is presented for each climate season of the year. The difference between the reliability curves is caused by the increase in the number of cooling towers necessary to keep the nominal output of the power plant. The reliability curve named summer II is related to use of the evaporative cooling system installed in the air inlet of each gas turbine. It is possible to verify that the plant reliability decreases very fast along the operational hours.

The basic pieces of equipment of the power plant, such as the gas and steam turbines, HRSGs and condenser must always be operational to allow electric power generation. In Fig. 11 the reliability curve of the main equipment of the power plant (two gas turbines, two HRSGs and one steam turbine), considered as series system configuration, is presented. Through the comparison of Figs. 10

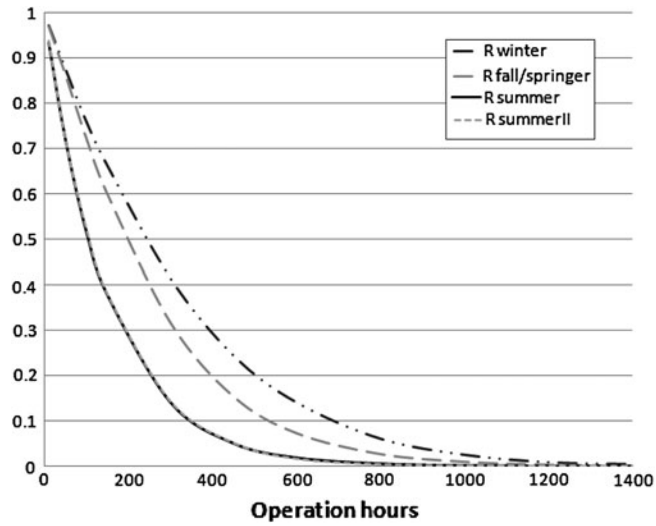
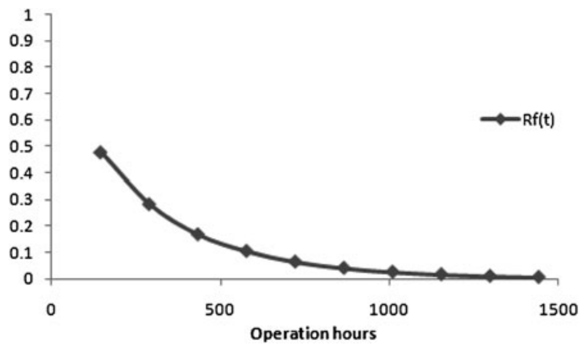


Fig. 10 Power plant reliability

Fig. 11 Gas turbines, steam turbine, hrsgs and condenser combined reliability



and 11 it is clear that the cooling tower reliability has great influence on the power plant reliability.

Although the main pieces of equipment have a very stringent maintenance policy, defined by the equipment manufacturers, some auxiliary systems that are not analyzed by the manufacturers can present failures that cause the performance reduction or even equipment shut down. As present by Carazas and Souza [4] and Carazas, Salazar and Souza [6], those auxiliary system must have their maintenance policy re-evaluated based on RCM concepts.

For the present analysis, the reliability of both gas turbines and HRSGs considers the improvement in the auxiliary system maintenance policy and the shape factor (β) of the Weibull distribution used to model their reliability is close to 1.

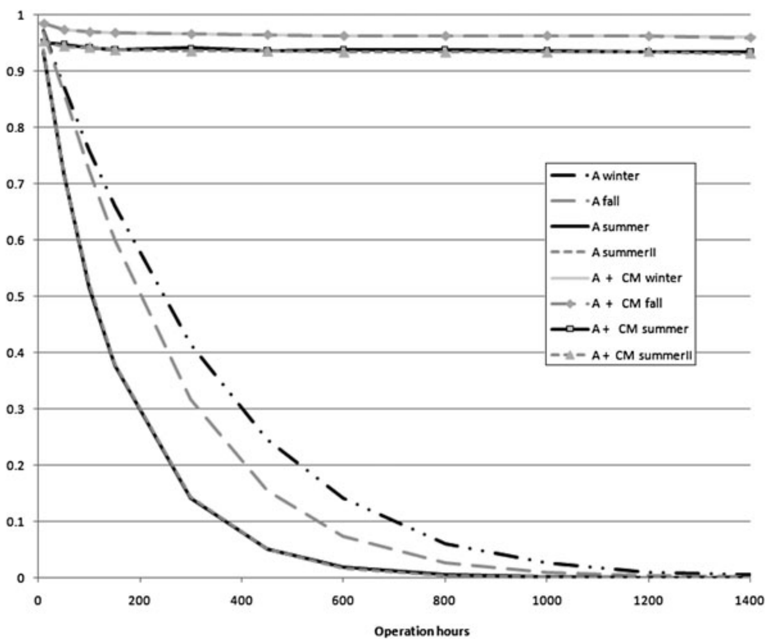


Fig. 12 Power plant availability

The steam turbine and condenser have their reliability modeled by exponential distributions indicating that their maintenance policy is considered sufficient to reduce the auxiliary systems failure frequency.

Another important performance index related to complex equipment efficiency evaluation is the availability index.

In Fig. 12 the availability index of the power plant is simulated considering the maintainability distributions presented in Table 7. The results are numerically presented in Table 8.

The power plant availability is calculated based on the relation between mean time to failure and mean time to repair, expressed as:

$$Availability = \frac{MTTF}{MTTF + MTTR} \tag{3}$$

The availability of the power plant is around 95% and that value is less sensitive to seasonal effects than the reliability index.

All calculations are made considering 1,440 h of continuous operational, corresponding to two months, once bimonthly the main pieces of equipment are subjected to predictive inspection aiming at detecting possible failure modes development.

The thermal power plant under analysis is normally used to complement the base generation of hydroelectricity. However there are seasons during the year,

Table 8 Comparison of power plant reliability and availability

Season	K	Reliability				Availability			
		Operational hours				Operational hours			
		168	336	720	1,440	168	336	720	1,440
Winter	8	0.5334	0.3233	0.1087	0.016	0.96	0.9587	0.9577	0.9554
Fall	9	0.5259	0.3054	0.0954	0.014	0.9563	0.9596	0.9568	0.9565
Spring	9	0.5259	0.3054	0.0954	0.014	0.9563	0.9596	0.9568	0.9565
Summer	10	0.273	0.0878	0.0072	0	0.9338	0.9302	0.9247	0.9226
Summer II	10 + EV	0.2794	0.0853	0.0067	0	0.9338	0.9344	0.9269	0.9235

usually in summer, that the hydro power plant lakes levels are low due to variations in the rainfall. By that time, the thermal power stations must generate the nominal output and any unexpected loss of performance can affect the power supply for some regions. During summer, the reliability of the power plant is strongly affected by the cooling towers units' reliability once all 10 units must be operational to provide plant nominal power output.

Furthermore, even with an incomplete failure database for the cooling towers, the plant unavailability data indicate a great number of failures in the cooling tower system.

Based on those results it is possible to select the cooling tower system as the most critical subsystem for the power plant. For that system a more complex analysis should be executed aiming at improving its reliability.

3.3 Cooling Tower System Reliability and Availability Improvement

The cooling tower unit can be considered mainly a mechanical system as for reliability and maintainability analysis. The operational conditions of the power plant, mainly associated with quality of recirculation water, and even the development of some specific failure modes of some components, such as fan unbalance, can affect the performance and degradation of some cooling unit components, mainly the gearbox. In reliability analysis this is named dependent failure modes.

The main forecasting methods of analysis previously outlined in the previous chapters of the book, allow highlighting the dependencies between failures. However, the relative difficulty of anticipating all these dependencies leads to multiply the approaches and to use more specific methods.

The advantages of these various methods, classified according to level of its effects on a set of interacting systems are summarized in Table 9, where a + sign gives a rough and qualitative indication of interest of each of these methods.

Table 9 The interest of predictive analysis methods in dependent failures, Guimarães [11]

	FMEA	FTA	BFCM	ETA
External initiators				
Internal initiators			+	+
Elementary systems				
Functional dependency			+	+
Common equipment dependency			+	+
Physical interactions			+	+
Human action dependency			+	+
Components				
Functional dependency	+	+	+	+
Common equipment dependency	+	+	+	+
Physical interactions	+	+	+	+
Human action dependency		+	+	+

The only method listed in the previous table that was not considered in the previous chapters is the Brief Failure Component Method (BFCM). The BFCM allows usually only for evidencing the simple failures and therefore must be completed by researching failure combinations that lead to undesired events. BFCM is the method that enables through inductive means, the determination of these failure combinations after carrying out FMEA. The set of abnormal operations (or failure modes) of a system is hence determined, Guimarães [11].

According to Guimarães [11], this method was created to analyse the safety in Concorde and Airbus aircraft. The research developed in nuclear fields contributed to the development of the method, notably theoretical fundamentals. The method is characterized by the introduction of certain specific concepts: brief internal failures, brief external failures, and brief global failures. The idea of "effects" allows for the connection between failures of abnormal operation, unwanted events, etc.

Numerous other specific methods have been developed for dependent failure analysis. These can be grouped into three main families:

(a) specific analyses of initiator events of dependent failures;
(b) analyses of generic causes; and
(c) analysis of operational experience

The specific analysis of initiator events of dependent failure aims to analyze in detail the effects of external initiators (aircraft collapse, earthquakes, etc.) or internal events (sizing accidents, loss of electrical panels, pipe ratchet ting, etc.) of the system, to limit the consequences and make them acceptable. It allows for the adequate sizing of elementary systems and the affected components.

The analysis of generic causes aim at predicting the occurrence and effects of common cause failures brought about by one or more generic causes. Among these analysis the following can be listed:

(a) prediction analysis of generic causes where the analyst seeks to identify system failures guided by the classification previously outlined; for the sources of potential failures, the analyst verifies the constructive provisions which enable the confrontation of these failures;
(b) zone analysis, that aim to analyze the dependencies between failures resulting from "geographical" location of certain components or subsystems; using:

- installation procedures
- physical array of components
- identification of possible failures; and
- identification of maintenance errors.

(c) analysis of human factors, which due to their importance are subject to special methods.

The detailed analysis of operational experience is a non-exhausting source of dependent failures. It requires a standardized and systematic gathering of all the incidents affecting systems and components. The wealth of this analysis depends very much on the quality of data gathering.

For the probability calculation of dependent failures and of common cause, two methods can be identified:

(a) explicit methods based on a precise knowledge of the causes of such failures, that allow the application of the general formula of conditional probabilities; and;
(b) parametric methods that are based upon statistical failure modelling, without research and listing of the causes.

Three parametric methods that deal, overall, with common cause failures can be indentified:

(a) parameter method β, Fleming, Kelley and Mosleh [9];
(b) multiple Greek letter method, Fleming, Mosleh and Deremer [10]; and
(c) shock method, Atwood [2].

The results of the operational experience analysis of nuclear power plant safety systems show the relatively high proportion of dependent failure incidents and the incidents that effectively occur. These demonstrate that the gains in availability or reliability achieved as a result of redundancies are inferior to those predicted theoretically. Therefore, for the more common components in safety systems, such as pumps, valves, engines, the gain can be estimated from 5 to 20 for a redundancy order of 2. An increase in redundancy by the order of 3 or 4 leads to very limited additional gains, maximum of 2–10. Beyond this, gains are marginal.

As an indication, and by no means exhausting the matter, a few generally applied preventive means for reducing the impact of these failures are, Guimarães [11]:

(a) During design phase:

- prevention of initiators that trigger failures of common cause, constructive dispositions for the control of:
  - environment and its aggressive factors
  - accidental environment originated within the installations, main plausible or hypothetical accidents considered in the design in a conservative manner.
- prevention of dependencies within elementary systems:
  - physical and geographical separation of redundant systems;
  - separation of safety functions assured by different systems;
  - functional diversity and system diversity;
  - different auxiliary systems;
  - allowance for periodical testing;
  - optimization of man–machine interface (automation of human actions that cannot be carried out with sufficient reliability within given time constraints; clear, precise and simulator proven, operational procedures, consideration of predicted human errors);
  - systematic research of dependencies through prediction analysis methods;
- prevention of the dependency between components:
  - physical and geographical separation of redundant systems;
- diversity of redundant components; (different design and manufacturing parties);
  - safety failure modes of the components
  - allowance for periodical testing;
  - systematic research of dependencies through prediction analysis methods;

(b) During Operational phase:

- prevention of dependent failures through systematic and detailed analysis of all the incidents and accidents upon installations and within similar installations
- prevention of human errors:
  - education, training and motivation of the operators, availability of several operators, incident diagnostics carried out by two independent and separate teams, and using separate means;
  - suspension of simultaneous maintenance carried out on important components, maintenance log carried out on important components controlled by other teams.

As for cooling tower analysis, once the system is already built, the plant operator can not modify the basic power plant design. Due to physical space problems it is not possible to increase the number of cooling towers units aiming at increasing the number of redundant units.

Another possibility is to change the cooling tower design aiming at reducing some components failures. Due to some inconsistencies in the power plant failure

databases a more detailed failure analysis that would support any change in the unit is not presently feasible. In case of improvement in the database registers they should support more detailed FMEA analysis providing more information to define possible design changes.

The only possible way to reduce the frequency of failures in the cooling tower units is to improve the maintenance strategy.

3.3.1 RCM Concepts Applied to Cooling Tower Availability Improvement

Component manufacturers and suppliers tend to recommend a very conservative and costly maintenance approach. Changes in the power system market has led to a shift from technical to economic driving factors, including the maintenance planning with the aim of the increase of the operational lifetime and reduce costs.

Modern engineering systems are ideally designed for profitable operation throughout their service life in compliance with given requirements and acceptance criteria typically related to the safety of the personnel and the risk posed to the public and the environment. For ensuring this, it is necessary to control the development of deterioration processes by appropriate planning and performing of inspections and predictive maintenance actions. The predictive maintenance aims to reduce preventive maintenance tasks for critical components, this policy allows the reduction of unexpected failure occurrences that cause the system unavailability and are usually very expensive to repair.

The RCM philosophy supports the selection of maintenance tasks for critical components. In this way and based on the failure rates of these components, maintenance tasks are selected as shown in Table 10. The maintenance frequency is calculated to ensure a minimum reliability of 80% (for each critical component), calculated according to Eq. 2. The result of the analysis is displayed in the third column of Table 10.

A specific analysis can be developed for the cooling tower units' gearbox once this component usually presents a great number of failures due to the efforts imposed by the fan rotation.

The gearbox can present gear teeth failures due to transient overloads or even due to fatigue or even bearings failures due to problems with lubrication oil.

For this component it is recommended the use of condition monitoring based on vibration analysis. Based on velocity vibration measurements (usually expressed in mm/s RMS) the maintenance team can detect fan unbalance or misalignment, failure development in gear teeth and even early failure detection in rolling bearings. The vibration analysis could be complemented with oil analysis aiming at detecting the presence of debris that could be an indicative of gear tooth or bearing wear out. In Fig.12 it is presented the power plant availability considering the condition-based monitoring tasks applied to cooling tower units, without considering corrective tasks.

Table 10 Maintenance schedule for counterflow cooling tower, Carazas and Souza [5]

Description	Comments	Frequency of inspection activity
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place.	
Check tower structure	Check for loose fill, connections, leaks, etc./inspect and readjust the unions in case they have lost the adjustment due to vibration. Inspect the presence of cracks or deformations in the structure.	Monthly/
Bimonthly		
Fan electric motor condition	Check the condition of the fan motor through temperature or vibration analysis and compare to baseline values.	Monthly
Check fan blades	Check for excessive wear and secure fastening	Monthly
Flexible shaft	Check the condition of the flexible shaft fan through temperature or vibration analysis and compare to baseline values.	Monthly
Check motor supports	Check for excessive wear and secure fastening	Monthly
Motor alignment	Aligning the motor coupling allows for efficient torque transfer	Monthly
Check drift eliminators, louvers, and fill	Look for proper positioning and scale build up	Monthly
Inspect nozzles for clogging	Make sure water is flowing through nozzles in the hot well	Annually
Check bearings	Inspect bearings and drive belts for wear. Adjust, repair, or replace as necessary.	Annually
Motor condition	Check the condition of the motor through temperature or vibration analysis to assure long life.	Monthly
General recommendations for predictive and preventive maintenance		
Vibration	Check for excessive vibration in motors, fans, and pumps	
Test water samples	Test for proper concentrations of dissolved solids, and chemistry. Adjust blowdown and chemicals as necessary.	
Check lubrication	Assure that all bearings are lubricated per the manufacturers' recommendation.	
Clean tower	Remove all dust, scale, and algae from tower basin, fill, and spray nozzles.	
Piping	Check the leaks or excessive corrosion. Monitor the pressure of operation of the system to avoid very high pressures, and inspect the filter system to prevent the entry of corrosive agents	
Thermographic Analysis	Check and monitoring motors, bearing and pumps	

4 Conclusions

This chapter presented a reliability-based analysis of a thermal power plant aiming at detecting the critical components as for its long-term reliable performance.

According to the standards associated with in field performance analysis of thermal power plants, the reliability evaluation tests can be performed during plant commissioning but the codes do not specify how to develop those tests and how to analyze and to present the tests results.

The reliability and availability of a combined-cycle thermal power plant is presented focusing on defining the reliability distributions of plant main pieces of equipment. Those distributions were defined based on failure data recorded in the power plant maintenance record.

The cooling tower units are selected as the most critical pieces of equipment considering the power plant operational profile. For that piece of equipment some changes in the maintenance plan are suggested based on the RCM philosophy.

In order to increase the use of reliability concepts in thermal power plant performance analysis it is expected that the presence of regulatory framework can have a determining influence on the use of risk and reliability methods in practice.

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